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OBSERVATION OF THE EARTH BY RADAR

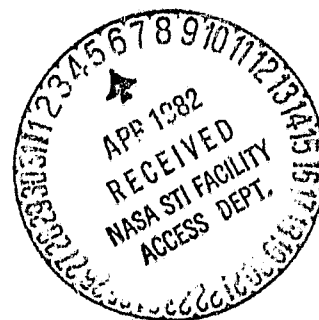
C. Elachi, A. Fontanel

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OBSERVATION

OF THE EARTH BY RADAR - by Charles Elachi and Andre Fontanel.

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Andre Fontanel, Doctor of Science, Director of Research at the French Petroleum Institute, directed the tele-detection activities of the I.F.P. from 1970 to 1980.

Charles Elachi, researcher at the Jet Propulsion Laboratory of the California Institute of Technology in Pasadena, is in charge of the program for space research using radar.

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The radar flown on the Seasat experimental satellite in 1978 permitted the gathering of Earth images by a new procedure. The radar images being formed on the basis of a beam emitted from the satellite, they are no longer dependent upon atmospheric conditions. This gives rise, then, to a very effective means of observing the Earth by satellite.

The analysis of information gathered opens vast domains of applications, both on the land, in the interests of geology for example, and over the oceans. In fact, through the use of SEASAT - and it is this which renders the satellite worthy of its name -

*Numbers in margin indicate pagination in original foreign text

observation of the seas enters a new era, full of promise for the oceanographers : the radar images enable them to follow the evolution of waves on the ocean and the movements of polar ice.

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Since 1965, images taken from space have contributed to the increase of our knowledge of the surface of the Earth. The Landsat satellites, the first of which was launched in 1972, furnish images whose spatial resolution is on the order of 80 meters. They have some applications in cartography in general and in geological cartography in particular (petroleum and mineral exploration); they permit establishment of forest inventories; evaluation, and even forecasting, of harvests (see "Research" Nr. 96, pg. 40, January 1979). Future generations of tele-detection satellites, such as the French SPOT which will be launched in mid-1984 or the American Landsat D which will be put into orbit in 1982-83, should improve this performance even more since their geometrical resolution will be respectively 10 meters (the SPOT panchromatic mode) and 30 meters (Landsat D thermal mapper).

The spectral domain in which the images are taken is limited, either by technological constraints or by constraints related to atmospheric absorption. The images taken by Landsat are situated in the visible domain and close to infrared; the NOAA meteorological satellites and the HCMM satellite, launched by NASA in April 1978, furnish images in the thermal infrared, which is to

say wave lengths between 8 and 14 microns, band of wave lengths which corresponds to the energy radiated by a body at ambient temperature, being some 300° K. The Nimbus meteorological satellites function in the zone of centemetric waves, but the images obtained by virtue of their radiometers (apparatus serving to measure the temperature of illumination in the wave band being considered) are of very low spatial resolution.

The Seasat satellite was launched by the USA in June 1978. For the first time it was possible to obtain, from space, images of the Earth taken by means of a radar. Besides a lateral synthetic aperture radar (SAR), Seasat was equipped with a series of transducers, among which a scanner operating in the visible and infrared, at 0.52 to 12.5 micrometers (VIRR), a four-frequency radiometer covering between 6.6 and 37 GHz (SMRRR); it permitted the capture of temperatures of illumination of the ocean surface at close to 1° C.; a diffusometer at 14 GHz which gave the direction of the surface winds at $\pm 20^{\circ}$ and an altimeter (ALT) at 13.9 GHz which could measure the variations in altitude and the height of waves within close to 20 cms. The Seasat mission lasted for one hundred days, during which the images of millions of square kilometers of oceans and dry land were taken. However, these images could only be obtained in the Northern Hemisphere and in Eastern Europe, notably, for the very great output of data rendered onboard recording impossible, and indispensable the direct transmission to Earth stations. The latter were not numerous and existed only in Canada, the U.S.A. and in England

(Oakhanger). For this reason, the Seasat images concerned only the zones covered by these stations, and each corresponds to a circle of about 4,000 kms in diameter. The images were obtained on the continents, but also for a part of the Pacific and a part of the Atlantic. The duration of the mission was shortened for, as the result of an onboard short-circuit, the Seasat radar abruptly terminated transmissions.

All-Weather Images

The advantage of images obtained by radar is related to the properties of wave lengths in the electro-magnetic spectrum utilized: in effect, the radars operate at a wave length generally situated between 1 cm and 100 cm.; Seasat was transmitting on 23 centimeters. These values are well above the wave lengths of the visible domain, centered around some 0.50 micrometers or at those of the infrared which run from 1 to 14 micrometers. The propagation of radar waves is not subject to the same hazards as luminous waves; in particular, the propagation of these waves is not disturbed by drops of water in suspension in the atmosphere; therefore radar waves traverse clouds, while the latter are obviously an obstacle for luminous waves and even those in the infrared. Better still, the radar image does not require that the object be illuminated by sunlight. In effect, radar, which is an "active" apparatus, itself sends its own electro-magnetic waves, which are then reflected or diffracted by the various objects. In

making variations in the direction following which the latter are "illuminated", it is possible to obtain different images, particularly over broken ground; in addition, the radar images are always obtained with oblique lighting; the angle of incidence is included between 20° and 80° . Radar images are capable often enough of casting light on minor variations in the slope of terrains; they are, therefore, well adapted to studies of topographic and geomorphological character; in effect, the latter influence strongly the energy of radar echos, since a variation of a few degrees in the slope of a surface can easily cause a variation of the energy of the radar echo by a factor equal to two or more, and this in particular at small angles of incidence, inferior to 30° . Such strong variations in reflected solar energy are not observed in the case of aerial photography. On the other hand, when the angles of incidence are situated between 30° and 70° , there are other parameters which become preponderant since the reflected radar energy depends principally on the condition of the rocky surfaces and their roughness.

Several hours of calculation for one image

There are two distinct types of radar: the radars known as real /illegible/ antenna SLAR, (Side looking airborne radar) and the radars with synthetic aperture SAR, (Synthetic aperture radar). In both of them the radar beam is oriented perpendicularly to the line of flight of the aircraft /illegible/ or the satellite

and has very roughly the form of a cone whose apex angle of aperture is all the smaller when the transmitting antenna has large dimensions (Figure 2).

Figure 1. Images taken from the various satellites cover varied domains of the electromagnetic spectrum. Radar waves are situated in a domain of wave lengths far distant from the visible, and even from the infrared, the images obtained by this procedure are for this reason far different from those of the oceanic observation satellites like Landsat. These three images represent the region of San (illegible) Swell, in Utah, seen by Seasat (A) and by Landsat (B). The image (C) is a combination of the preceding two. Some geometric corrections have first been applied to the two images, A and B, in order to render them superposable; they were then combined in a computer, and the result (C) associates the spectral richness of Landsat with the geometric resolution of Seasat and its faculty for differentiating the rocks as a function of their surface condition. Thus, even the lithological units which cannot be isolated in the Landsat image appear with color tones of a different model; in the composite image the colors are totally arbitrary as also those of the image (illegible) (B).

(Print, NASA JPL).

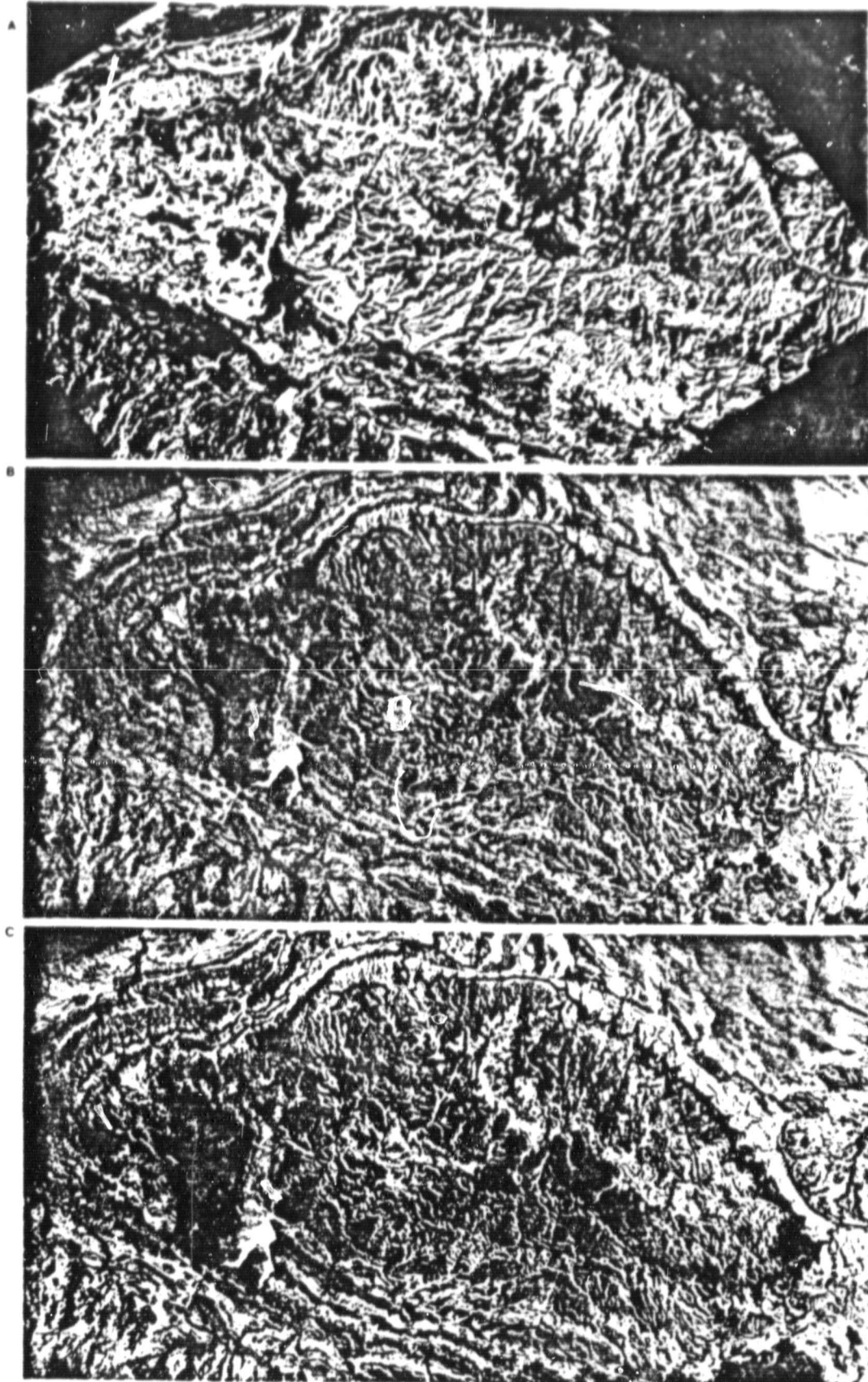


Figure 1

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The radar image is sensitive to variations in slope and the surface conditions of the terrain

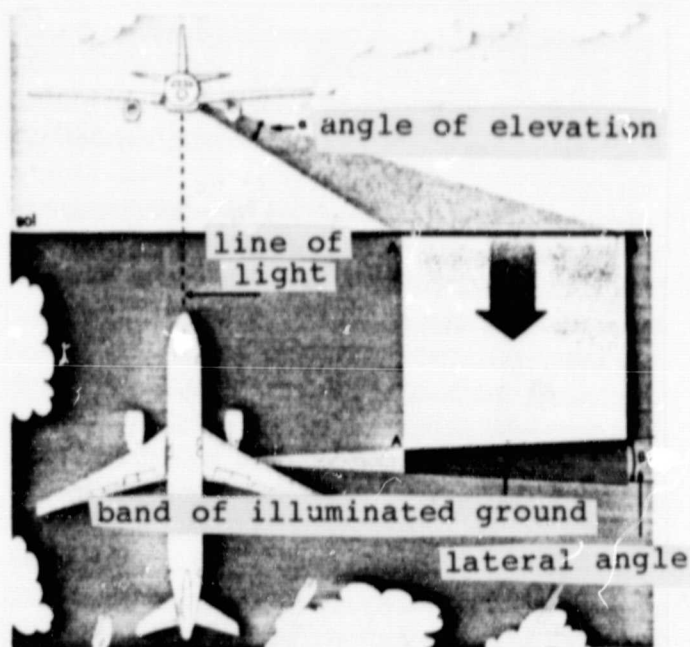


Figure 2. The apex angle of aperture of the beam emitted by the radar in the form of a cone is, in the horizontal plane, on the order of plane angle (θ , in the direction of movement of the flying platform) and some 20° to 60° (α in the vertical plane). The horizontal angle being small, its value in radians is approximately that of the ratio of the wave length utilized to the length of the radar antenna. The radar transmits toward the ground, in this cone, several thousand electro-magnetic impulses per second. By reason of the advance of the flying platform, the successive bands of ground illuminated by the radar (AB in the figure) follow each other in time, and the "coverage" of the terrain being studied is accomplished in this manner.

In the case of radars with real antennae, the image of the Earth is obtained simply by an optical representation of the energy of the echoes received in the course of time, by placing side by side each image of the several illuminated bands (AB) on the ground. It is clear, from Figure 2, that the geometrical resolution, that is to say, the ability of the radar to form clear images of small objects, is degraded as the range increases; the illuminated band at B is wider than at A. This is still acceptable, when the radar is flown in an aircraft flying at several thousand meters altitude; by way of example, the geometrical resolution of a radar with real antenna operating on a wave length of 3 cm with an antenna 5 m long is on the order of 30 meters at 5km distance and of 60 meters at a distance of 10 km. This type of operation is completely unacceptable on board a satellite which orbits the Earth at several hundred kilometers altitude since, with the characteristics mentioned above, the resolution on the ground would be some 4,800 meters (!) at 800 km; it would only be possible to distinguish objects having a size of more than 4 or 5 kms. The dimensions of the antenna can always be increased to improve the resolution, but a more elegant solution consists in utilizing the synthetic aperture technique. In this case, the processing of the signals becomes more complex, since not only the amplitude of the echoes, but also their phase, must be taken into consideration. The image of the over-flown surface is, therefore, reconstructed by digital or optical processing of

the amplitude of the echoes received, as a function of the time of their shift in frequency in relationship to a reference signal, which is to say, the Doppler effect (Figures 3 and 4).

The several points on the ground situated at equal distances from the radar are distributed over a series of spheres centered on the radar. The intersection of these spheres with a plane surface gives a series of concentric circles on a point situated at the nadir of the radar. All the echoes returned by the objects situated on each of these circles arrives at the radar at the same instant. In addition the various objects which are found on the coaxial cones having the line of flight for their axis and the radar as their apex give rise to identical Doppler shifts. Each point on the ground is represented in the radar image by a luminosity which is proportional to the energy contained in the echo which it has generated. Thus, if the information contained in the different Doppler effects is combined with the energy of the received signals as a function of time, each point on the ground can be localized and identified without ambiguity. The geometrical resolution of this system is a function of the precision with which the different shifts in time can be measured between successive echoes as well as the different phase shifts relative to two neighboring objects.

In reality, the problem is a little more complex: the radar emits a signal composed of successive pulses in such a manner that it is able to measure the different round-trip time of the signals; but to obtain the Doppler information without any

ambiguity, several successive echoes must be taken into account, echoes which correspond to numerous different impulses. In the measure that the platform, be it aircraft or satellite, over-flies a region, the recording of the synthetic aperture radar represents, thus, by virtue of the succession of all the echoes which are recorded, taking into account their module and their phase, the complete "history" of the variations of the distance of the radar from the different reflective points on the surface. All of this data must then be subjected to optical or digital processing before it is possible to obtain an image and thus make correspond, without any ambiguity, each reflective point with its corresponding point in the recording. This operation is accomplished either by digital or optical processing. The digital processing necessitates a very large number of calculations which include convolutions and Fourier transforms. The reconstruction of a SEASAT image over 100 x 100 km necessitates several hours of calculations on large machines (CDC 7600) and up to 40 hours on machines of medium power.

Optical processing is simpler to use. It can be shown that the raw radar recording is similar to a hologram of the ground surface; the optical transformation consists in generating the corresponding image by means of a well known process of coherent optics. (Figures 3 and 4). Each point on the ground which returns radar echoes gives rise, on the raw recording and after synchronous detection, to a series of "pulses" which are translated on film by a series of successive bright and dark

interferences, stretched out in the direction of the movement of the radar. When the photographic film is placed in the beam of coherent light of an optical correlator, the light which traverses it is diffracted, each interference zone acting as an element of a Fresnel lens, and in the focal plane can be observed the reconstruction of the object which originated the interferences.

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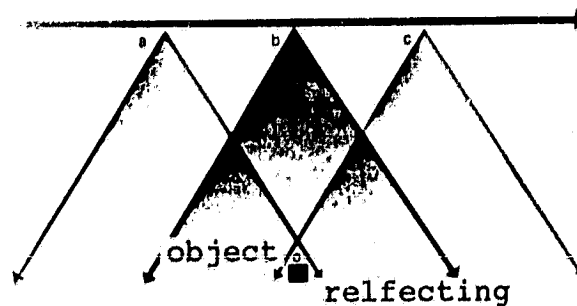


Figure 3. In the case of a synthetic aperture radar, the raw recording is formed according to holographic procedure. In flight, the radar successively occupies positions a, b and c from where it illuminates the object o situated on the ground. The distance ac represents the length of the so-called "equivalent" synthetic antenna. θ is the lateral spread of the beams, determined by the length of the antenna and the wave length used λ ($\theta = \lambda/\alpha$). Each point o on the ground returning echoes gives rise to series of interferences which can be recorded on magnetic tape or photographic film.

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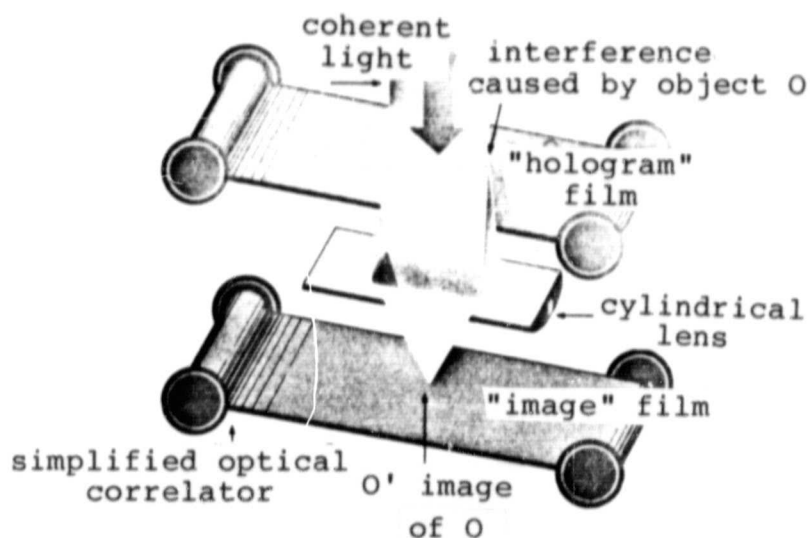


Figure 4. To proceed with the optical reconstruction of the image, the film on which the interferences were recorded is placed in an optical correlator and illuminated by coherent light. Object 0 gives rise to a series of interferences and is reconstructed as the image 0'

On the Space Shuttle

A radar quite similar to the SAR on Seasat will fly on the second mission of the Space Shuttle (1981-82). It will operate at a higher angle of incidence than Seasat (50° instead of 20°) and the processing will be done on board by optical means. Different regions of the world will thus be imaged and this experiment will have as its principal objective evaluation of the ranges of radars

in terrestrial orbits for geological cartography. The French organization GDTA (Group for Development of Aerospatial Tele-Detection) - 18, avenue E. Belin - 31000 Toulouse) will be part of the scientific team which will analyse the data acquired over Central Africa.

This SIR A radar will be utilized again on other missions of the space vehicle, but after having been modified in function of information gathered on the first mission: possibility of on board data processing in digital form, possibility of orienting the antenna to adapt the angle of incidence, etc...

The new generation of radars will also be able to take stereoscopic views, operate at two frequencies (L) and (X) and also in two polarizations.

This procedure of obtaining radar images, by virtue of its specificity, opens new fields of applications. On dry land the radar image is sensitive to variations in slope (topography), to the state of the surface of terrains (roughness) and to their water content. All these parameters permit, in particular, studies of a geological character. In effect, the folds and faults (Figure 5), the hydrographic network (Figure 6) generally appear very satisfactorily in the images. It must be pointed out, however, that the direction of flight in relationship to the length of the structures or the direction of the faults is of great importance.

The different behavior of rocks subject to exosion permits, also, elementary lithological differentiations (Figure 1). In effect, the technique of interpretation of the radar images alone does not at the present time allow direct identification of the terrains and to state, for example, that if such terrain is limestone, marble or clay. It is necessary to adjoin other information which can be furnished by, for example, multi-spectral images in the visible or infrared. The scale of the radar images, usually on the order of 1/100,000 (SEASAT offers a resolution of 25 m), is well adapted to geological exploration and, furthermore, it is this application alone to which it addresses its operational character.

Evaluation of water content

Radar imagery presents certain particularities which are inherent to it, for its tonality and its texture depend also on the dielectric properties of the objects. The dielectric constant is a number equal to 1 in a vacuum, in water, 5 to 7 in glass. This number is defined as the ratio between the capacities of the same condenser when the space between the plates is filled either with the material being considered - water or glass - or a vacuum. For objects seen by the radar, the dielectric constant is related to the water content, and its variations permit a study of the humid zones and the vegetation in general. The dielectric constant of water is very high and humid terrains correspond, on the image, to the zones where the energy of the echo is weakest. The

coefficient of return signal of water, because it differs so greatly from that of neighboring terrains, explains why water courses appear with such particular distinctness. Changes in vegetation are often distinguished with clarity (as well as the changes in slope of the terrains) in the neighborhood of river banks. In dry regions, when rivers have dried out, the strong return signal presented by the stones and sands of the riverbeds is transformed into strong contrasts on the image.

But the classification of types of hydrographic networks based on radar images the same as that which can be made from conventional photo-interpretation. As for studies of vegetation and cultivated areas, these are still only at their beginning.

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It is evident that radar images provide new information (Figure 7), but it is not yet known how to interpret them in a reliable way; in particular, it is not known how to sharply disassociate the effects of different parameters: humidity, roughness, height of the vegetation, etc... It is above all, in matters concerning the oceans, that the interest in radar is going to make itself felt. In effect, contrary to the continents, their surfaces are in rapid transformation, and it suffices that the sky be covered to render the usual photographic techniques incapable of following the evolution of these phenomena. As we have seen, the radar is independent of this constraint.

Study of the ocean wave

The first detection of ocean waves by the use of airborne radar took place in 1976. Since then numerous other oceanic phenomena have been brought to light with the help of radar. But a radar mounted in an aircraft is poorly adapted to study and follow these oceanic phenomena; they vary too quickly for aerial coverage, difficult to repeat at close intervals, unable to cover large enough surfaces. It was necessary to wait for Seasat in order to obtain, for the first time, a synoptic view of broad oceanic domains and the polar zones. In certain cases it has been possible to obtain, for a given zone, repetitive observations at three day intervals. Surveillance satellites equipped with lateral radars should permit, starting in 1987-88 (there is project ERIS I of the European Space Agency and a similar project in Canada) following their evolution on a world-wide basis, with a regular periodicity of observation on the order of a few days.

Figure 5. The Grand Canyon of the Colorado (Arizona) represents a major topographical accident. The Colorado River cuts deeply into the plateau, which rose progressively over the ages, to form this canyon, which is at present more than a kilometer deep. Horizontal sedimentary layers are section in the walls of the canyon. The hardest of these layers form vertical cliffs which can appear in the image as dark bands when they are not "lighted" by the radar beam. This is the phenomenon of inclined shadows which are at the origin of the largest part of the variations in tonality of the image. This image represents the south fold of the Grand Canyon, near to the village of the same name. The most important geological formations

(Kaibab limestone, Conconino clay, Redwall limestone, Tapeats clay) appear as dark bands in the "wall" of the canyon by reason of the inclined shadow of their vertical section. It can be seen here that the laws of geometry which control the formation of the radar image are more favorable than those of conventional optics. By reason of the effect of "slant", the abrupt flanks of the canyon which are oriented toward the radar appear as very brilliant spots in the image; this geometry causes significant geometrical distortions which interfere with the study of these flanks.
(Photo NASA - JPL)

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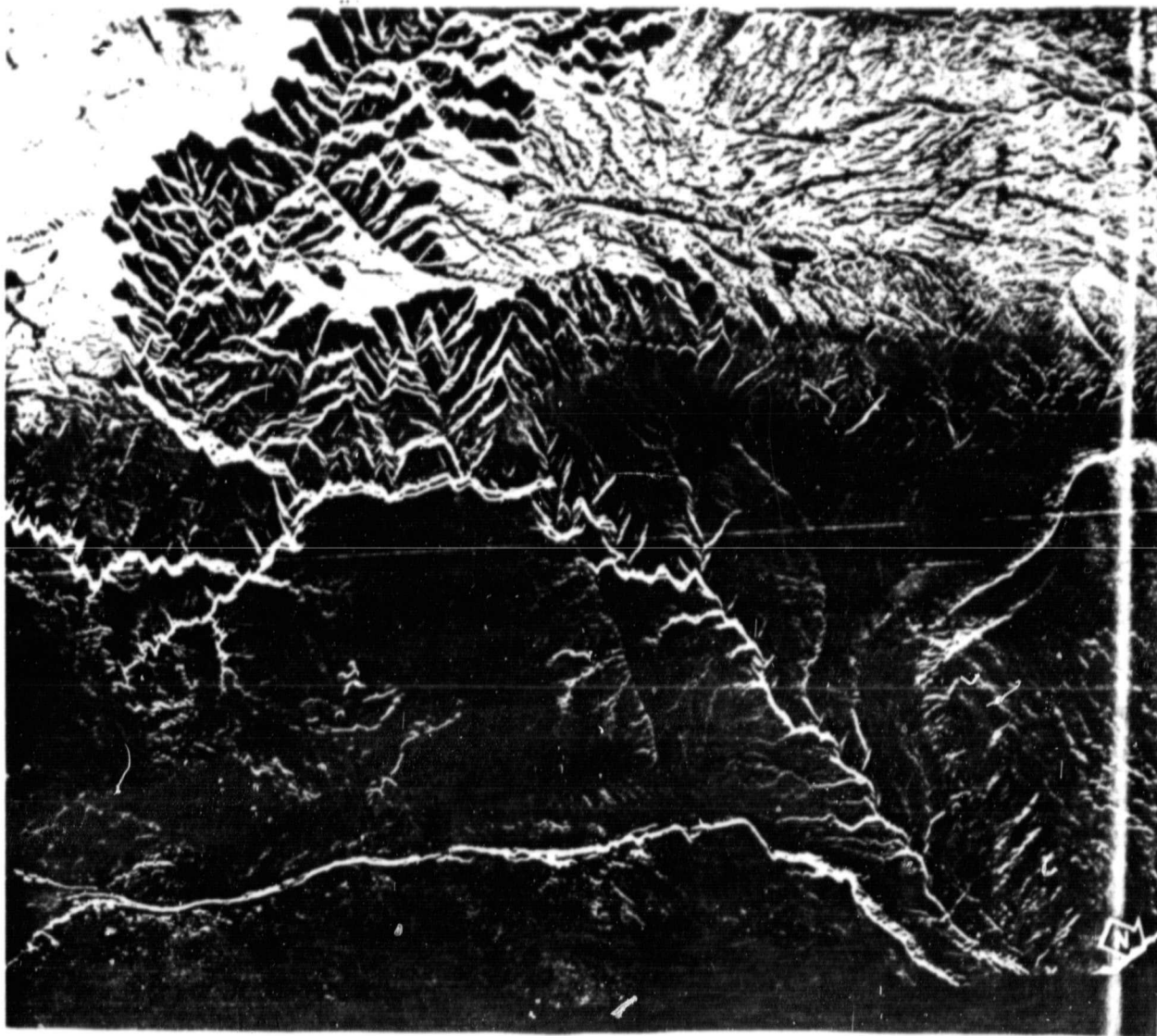


Figure 5

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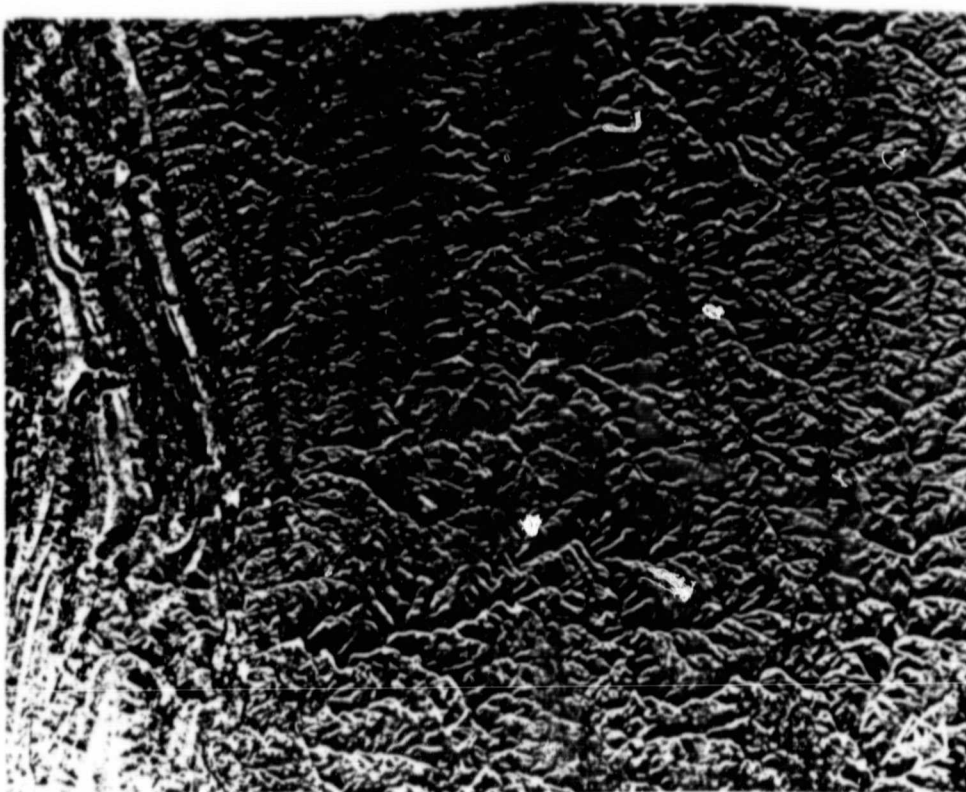


Figure 6. The region of Lockhaven, Pennsylvania, is heavily covered in vegetation and different networks of hydrographic canals which appear distinctly due to their differentiations in the topography. The density of the network is a good indicator of the nature of the rocks in this region. The dense network to the north (right, in this image) corresponds to the Catskill formation (red or brown clays) which is composed of relatively soft rock. The density of the network is lower at the south of the image. This is a cut up plateau of the "Mississippian Pocono" group (conglomerates and clay with some schist) which constitutes a relative resistant rock. The limit between the two types of rocks corresponds very precisely to the limit which appears in the image between the two types of hydrographic networks of different densities.
(Photo NASA - JPL)

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Ocean waves are transformed, in radar images, by regular and periodic variations in density (Figure 8). In fact, several surface phenomena, themselves modules by the propagation of waves or of surge, are responsible for the periodic variations of the coefficient of coherent return signals; the local inclination, the intensity and distribution of small waves; the capillary waves which are short wave length undulations of less the 2 cm and which are principally controlled by surface tensions; finally the orbital speed of the water particles (this is the speed of displacement of the particles of water themselves, which is different from the speed of propagation of the waves). The internal waves, corresponding to the "undulations" at the interior of the mass of water; undulations which can have different origins: variations in the thermocline, effect of the sea-bottom topography on strong tidal currents, etc... These waves, even though they exist in the thickness of the mass of water, can be observed by virtue of their manifestations on the surface and in particular by their effect on its roughness. The relatively large effects which are associated with these waves modify the spectrum of the little waves and capillary waves upon which they act. The exact mechanisms which control these modifications are still the subject of discussions; one of the hypotheses, proposed by several authors, considers that the heightened speed of displacement engendered at the surface of the water by the large amplitude of the internal waves could provoke the concentration of different

materials and, in particular, oily particles in certain zones of convergence, thus causing elongated bands along which the surface of the water would be smoother.

The second mechanism explaining the surface manifestation of these internal waves supposes, to the contrary, that the capillary waves have a larger energy in these zones of convergence which are due to the effects of the internal waves on surface currents; therefore these zones present a greater roughness, which is a contradiction to the first hypothesis.

In every case, when such zones are illuminated by the radar, following incidences far from normal, they appear in the images

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either as dark, in the case of smooth zones, or brilliant in the case of rough zones. The internal waves are often manifested in several groups; they have been observed in numerous regions, for example along the east and west coasts of North America, as well as on the European coasts. They can also be observed from aircraft, either by radar or by optical apparatus, but it is remarkable that in the course of only a few orbits of Seasat more internal waves were detected than in five years and tens of tens of airborne missions. These phenomena have also been observed with transducers working in the visible domain, or close to infrared, on images taken from the Landsat satellite, for example. On these radar images, the interior waves generally appear as packets of waves formed of a series of bands of convex shape, whose spatial wave length becomes shorter when the observer moves toward the

center of the curve. The length of crests can attain several tens of kilometers. The waves which are found in the frontal part of the packet have wave lengths on the order of 1 to 2 kilometers; the wave length decreases regularly toward the rear of the packet. These specific characteristics illustrate the interest of the Seasat SAR for the detection of certain dynamic phenomena of the oceanic surface. Radar images have also shown that in certain cases the topography of the sea bottom can be "reflected" on the surface (Figure 9).

The cartographical possibility and that of the dynamic study of sea ice in the polar regions is another important application of the SAR, presently in course of evaluation. A radar in orbit permits, in effect, to have a global and repetitive view of these regions and to study the movements, the structure and extent

of the sea ice. It was this project which was at the origin of the Canadian project for a future, radar-equipped satellite. The variation in color and the study of shapes permits identification of zones of free water as well as ice shelves and the different channels in the floating ice. At intervals of several days, displacements of ice running to 10 km a day on the average have been measured.

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Daily displacements of polar ice
running up to 10 kilometers daily

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Figure 7. This radar image was taken over the central part of the state of Iowa on August 15, 1978. In the evening of the previous day, a large storm traversed this region from west to east, on a wide front. On the radar image are traces left by rain in the zones where this storm fell; this refers to bands oriented from east to east-northeast. Here the wet parts return many more radar waves and appear in light tones. This is an extensively cultivated region and the fields create a checker-board pattern. The "color" of each field depends on the roughness of the surface, its water content and the vegetal cover

(Photo NASA - JPL)

To leave off stuttering

Thus, the Seasat radar has permitted, for the first time, obtaining images from space of dry land and the oceans, and that independently of atmospheric conditions and cloud cover. The overall preliminary works which were accomplished on the basis of these recordings indicates that "imaging" radars, when they are regularly in orbit, will provide an increase in the chances of discovering and inventorying terrestrial resources, as well as to better understand and survey the surface of the oceans. It can be hoped for example that this new method, by virtue of the information of a new type which it provides, will assist in completing the geological knowledge that can be acquired at the moment either on the basis of other methods of tele-detection (which operate in the visible or infrared domains), or by the entirety of other well known techniques utilized for thematic cartography. As for the oceans, it has already been stated, the radar is a unique means by which to "see" and study their surface on a global scale and without any constraint of a meteorological character.

Many fields of research are still to be pursued, not only for a better understanding and utilization of information of a geophysical nature which is contained in the "radar signature" of different objects, but also to learn to select, for each particular application, the optimal parameters for using the radar (geometry

of imaging, choice and extent of the spectral band, polarization). It is necessary, in effect, to underline how unusual are the operational applications of radar. The only people to have utilized airborne radars in a systematic manner are the mineral geologists and above all the petroleum geologists. Its other applications are at the first stutterings and this is certainly the reason why programs decided for future satellites (Spot in France, Landsat in the United States) are limited to the domains of the visible and infrared. It must be recalled, however, that the operation of radars of synthetic aperture on a satellite represent, as was mentioned, a major technical difficulty and that numerous advancements are to be accomplished, in particular the development of digital processing in real time, before these orbital radar can render operational service. It is for this that Space-Lab, orbital laboratory constructed in Europe, was built, and it will be launched at an early date by the American space shuttle. It will certainly be a unique test platform for bringing about the successful development of this research work.

The European Space Agency also plans to fly a radar in a satellite (ERS I) in a few years, but this program is not completely decided at the present moment. It is thought that the future use of several radar frequencies will increase the chances, as is also the case in the optical domain, of identifying objects (lithological units, different types of vegetation...). Radars in band L, of 25 cm wave length, such as Seasat, are above all susceptible to "surface accidents" in the range of 2.5 cm to 25

cm. With the addition of the X band (wave length neighboring on 3 cm, for example), the range of sensitivity will be extended to details of 0.3 to 3 cm, and for this reason the chances of differentiating objects will be increased. Radars flown on satellites will also permit an improvement in our knowledge of the planets. Radar is, for example, the only means of mapping Venus (and perhaps Titan), by reason of its permanent cloud cover behind which it hides.

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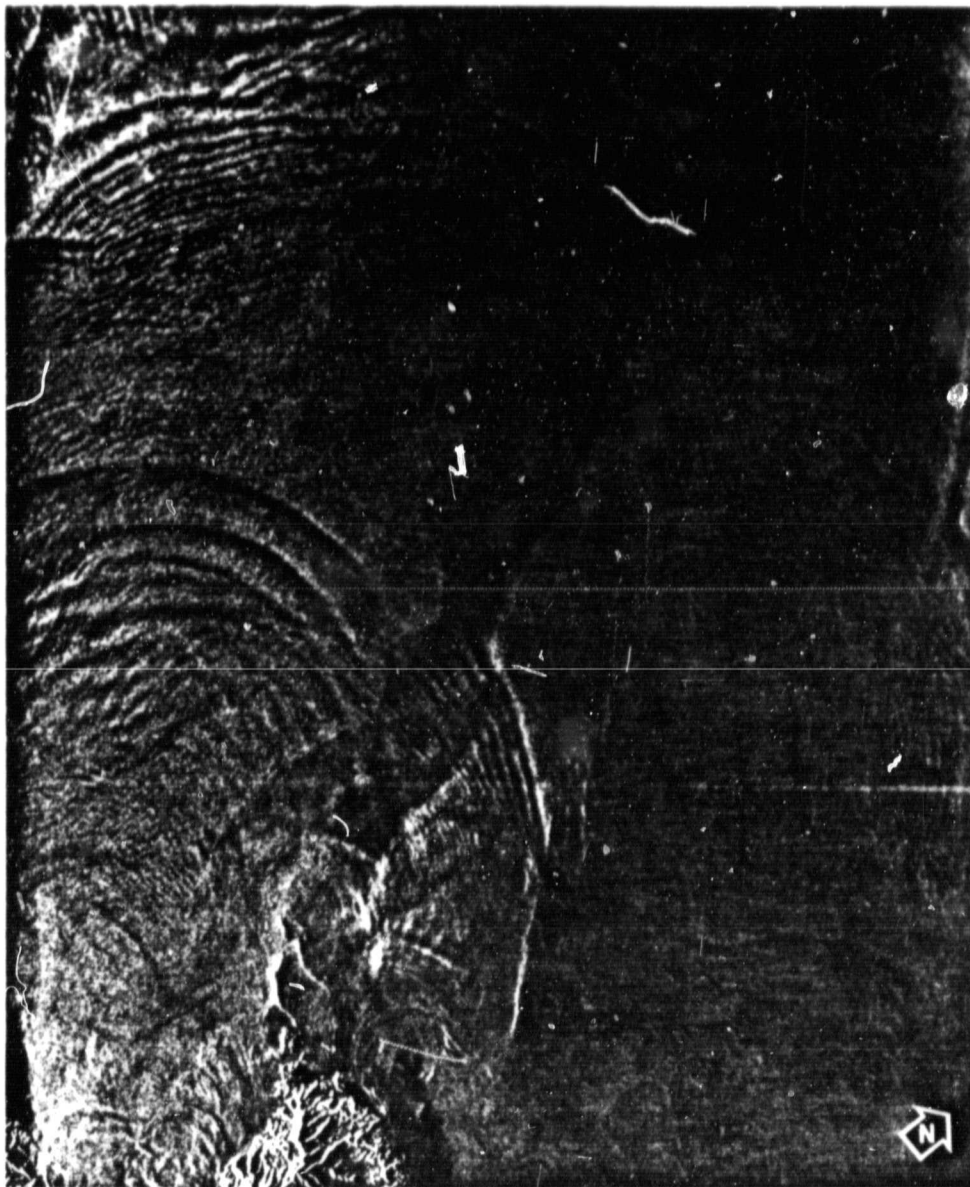
Figure 8. The Gulf of California is seen here, just to the north of the island of Angel de la Guardia. The three large aureoles, alternately bright and dark, correspond to the manifestations of internal waves as they appear on the surface of the ocean. The length of the crests runs from a few kilometers to more than 30 km and the distance between successive crests (wave length) can be several kilometers from the front part of the "packets". These internal waves have been observed quite often from Seasat, for example, in the Gulf of California and in Delaware Bay (east coast of the USA). They are sometimes explained by the effect of the strong tidal currents rising from the bottom at the level of the continental shelf.

(Photo NASA - JPL)

Figure 8.

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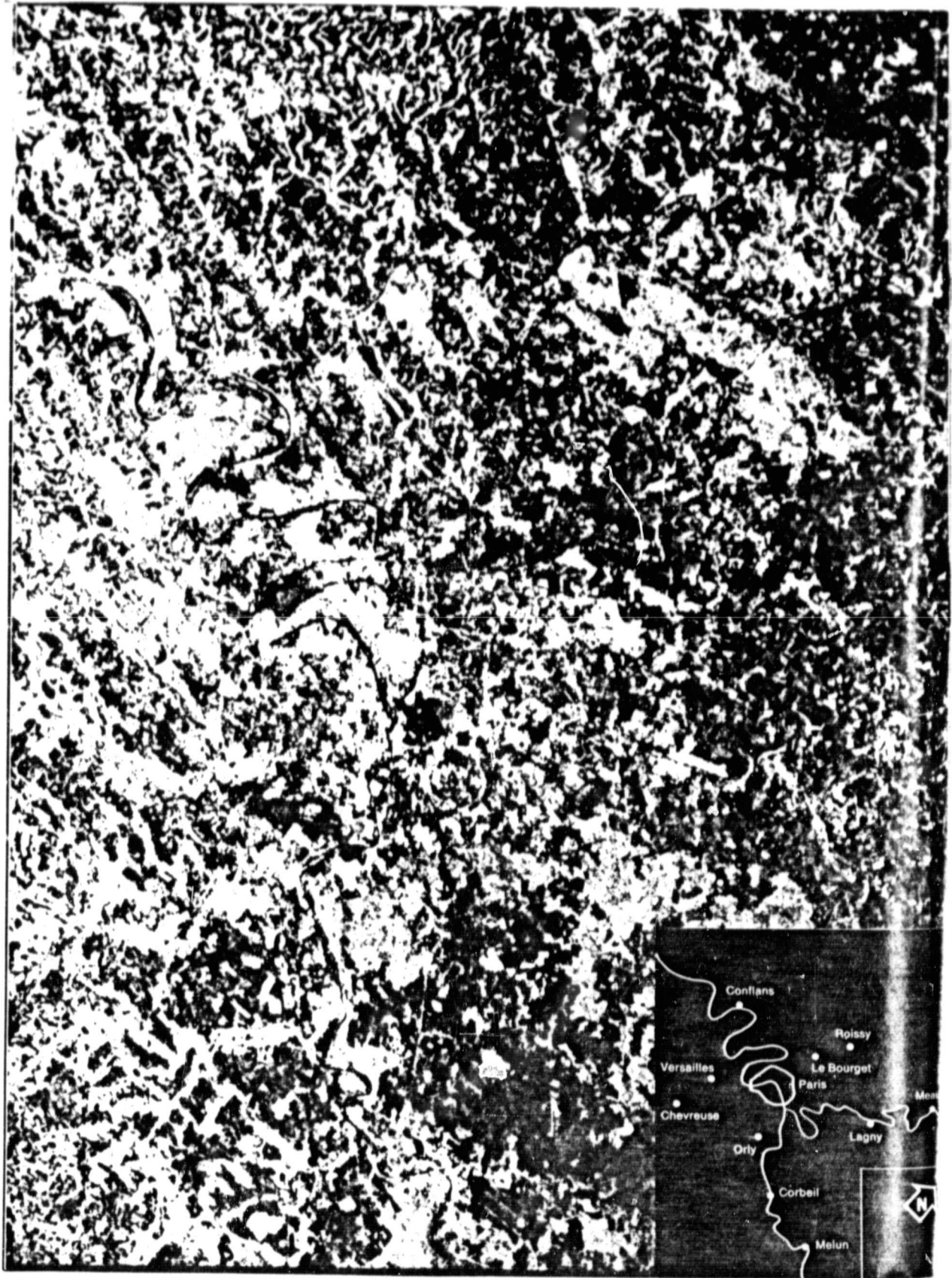
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In the rather shallow regions, accidents of the topography of the bottom can be reflected to the surface, owing to the disturbances which they bring to the flow of surface currents and capillary waves. The different ripples seen on this radar image, obtained on August 19, 1978 in the Pas de Calais, correspond to the sand dunes situated on the sea bottom and covered by several meters of water. The explanation of this phenomenon is still poorly understood. It must be underlined that no one had thought of this application of the radar before the launching of the satellite. This radar image gives here a very good representation of the field of the dunes by comparison to the available maritime charts, with which they have been compared; the continuity of the banks, covered by a depth of water running from 2-3 m up to about 15 m, is particularly remarkable. Boats appear in the image as bright spots and their wakes are visible. By reason of the Doppler phenomenon, well known in radar, the boats under weigh appear to be displaced in relationship to their wakes.

(Photo NASA - JPL)



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Figure 10

To know more about it

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